which $w_x = l_x/5$; only 20% of the available far-field energy falls in the central lobe (Fig. 2).

The theoretical limit to power in the central lobe occurs when the fill factor is 100% and the output of each diode is uniform (not Gaussian). This is equivalent to a plane wave with a diameter equal to the diameter of the entire array. The irradiance pattern from this is $(\sin x/x)^2$, and 81% of the total energy falls in the central lobe for large arrays.

In summary, the design of arrays of phase-locked lasers must include fill factor and beam truncation in any trade-offs to determine the optimum amount of beam expansion. Generally, the minimum spacing between the elements is dictated by mechanical or thermal considerations, and the burden of optimizing peak irradiance rests on the effectiveness of beam expansion and, of course, on the degree of coherence among the elements in the array.

I wish to thank Nicholas George and Stan Reinhold for helpful discussions.

References

1. B. D. Steinberg, *Principles of Aperture and Array System Design* (Wiley, New York, 1976).
2. C. P. Wang, "Master and Slave Oscillator Array System for Very Large Multiline Lasers," Appl. Opt. **17**, 83 (1978).
3. J. W. Goodman, *Introduction to Fourier Optics* (McGraw-Hill, San Francisco, 1968), p. 61, Eq. (4–13). Goodman's equation is a paraxial approximation in which R_0 has been replaced by z. Equation (1) is accurate for large angles off-axis.
4. The identity in Eq. (4) is stated for an odd number of terms; the right-hand side of the equation is also valid for an even number of terms in the series.
5. Although the output of an index-guided diode is not Gaussian, proper selection of the beam waist will generate a Gaussian beam whose electric field closely tracks that of a diode laser with a particular confinement factor. See W. Streifer, R. D. Burnham, and D. R. Scifres, "Symmetrical and Asymmetrical Waveguiding in Very Narrow Conducting Stripe Lasers," IEEE J. Quantum Electron. **QE-15**, 136 (1979), for a description of the electric field emitted from a diode laser.

Simultaneous output power and frequency stabilization of a Zeeman He–Ne laser

Ci-Ling Pan and P.-Y. Jean

National Chiao Tung University, Institute of Electro-Optical Engineering, Hsinchu, Taiwan 30050, China.

Received 19 November 1985.
0003-6935/86/091375-02$02.00/0.

Stabilized longitudinal Zeeman He–Ne lasers[1–3] ($\lambda = 633$ nm) have been used extensively as light sources in laser interferometers for dimensional metrology and also as an optical frequency standard in wavemeters for measuring wavelengths of other lasers. Two convenient methods for frequency stabilization of a longitudinal Zeeman He–Ne laser have been reported in the literature. In both methods, an internal mirror laser is placed in an axial magnetic field. Because of Zeeman splitting of atomic energy levels, the output of the laser consists of a pair of oppositely circularly polarized modes of which the intensity difference ΔI and beat frequency f_b depend on the positions of the modes on the gain curve. Either ΔI (Ref. 1) or f_b (Refs. 2 and 3) is used as the feedback signal to control the cavity length of the laser in these two methods. A frequency stability of <1 MHz ($<10^{-9}$) for an averaging time of 1 s and long-term reproducibility of ±1 MHz (~5 months) were reported.[3] The output power stabilities of laser stabilized by these two methods were not quoted, however. In this Letter, we present excellent frequency and amplitude stability results for a longitudinal Zeeman He–Ne laser by a new simple method in which a portion of the laser output intensity is monitored and fedback to control the laser tube length and hence stabilize the laser.

The basic principle of this method is as follows: It is well known that the major cause of frequency and amplitude fluctuations of a well-made internal mirror He–Ne laser is due to thermal dilation of the laser tube. The laser modes will drift across the gain profile as the temperature of the laser tube varies. The output of the laser would change accordingly. This general behavior is not changed by the magnetic field. Figure 1 illustrates schematically the variation of the total laser intensity I_{total}, ΔI, and f_b of our test laser with laser cavity length. Clearly stabilization of I_{total} by controlling the laser tube length results in an amplitude-stabilized laser. Now ΔI and f_b can both be considered frequency discriminators of the Zeeman laser. Examining Fig. 1, one finds that ΔI and f_b will both be stabilized at the cavity length for which I_{total} is a constant. That is, simultaneous frequency and amplitude stabilization of the Zeeman laser can be realized. The same method has also been used by previous workers to stabilize a two-mode laser[4,5] but not Zeeman lasers.

A block diagram of our stabilized laser is shown in Fig. 2. A single-mode coaxial laser tube 12.5 cm in length (axial mode spacing ~1.2 GHz) is inserted in a uniform magnetic field with a flux density of ~50 G. The power supply is a commercial potted type (Laser Drive) which regulates the discharge current to ±0.3%. A small portion of the laser output is detected and fedback as a current through a Kovar wire wound around a major portion of the laser tube to regulate its length. The beam splitter is not necessary for a laser with backbeam output. Care has been taken in positioning the detector to avoid optical feedback effect.[6] The control electronics is described in detail in another paper.[7] Briefly, it consists of a noise reduction and signal amplification network which removes a major portion of broadband noise from the power supply and discharge current fluctuations, a compensation network to compensate the thermal response of the system and increase the gain and phase margin of the servo, and a power amplifier circuit which converts the error voltage to heater power. A preheating cycle is also employed to establish the laser in an effective cooling mode.

While it is free-running, the test laser's beat frequency f_b varies from 210 to 640 kHz. For a stablized laser, the peak-to-peak fluctuation of f_b reduces to <200 Hz over a period of 1 h. This is illustrated in Fig. 3(a). For lack of an absolute frequency standard, such as an I_2-stabilized He–Ne laser, we have used Figs. 1(b) and (c) for calibration and estimated that the peak-to-peak frequency fluctuation of the laser $\pm\Delta f$ is <560 kHz. This corresponds to a relative frequency stability of ($<\pm 6 \times 10^{-10}$). Preliminary heterodyne experiments by beating the test laser with a homemade stabilized two-mode laser confirm the above measurement. To compare, we have also stabilized the test laser using ΔI or f_b as the feedback signal. The frequency stabilization results are almost identical. The relative amplitude stability of the laser is (±0.04%), as shown in Fig. 3(b).

It is well known that, in addition to variation in the cavity length of the laser, fluctuations in the discharge current also contribute significantly to laser amplitude fluctuations.[8] In

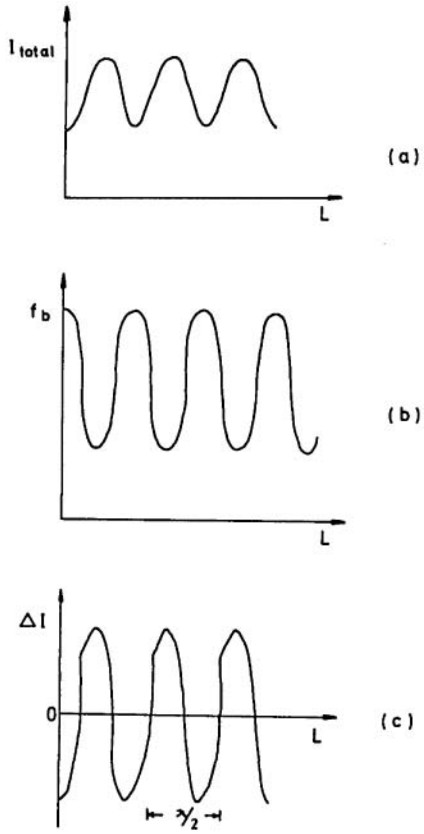

Fig. 1. Schematic representation of (a) I_{total}, (b) f_b, and (c) ΔI as a function of laser cavity length L. λ, wavelength.

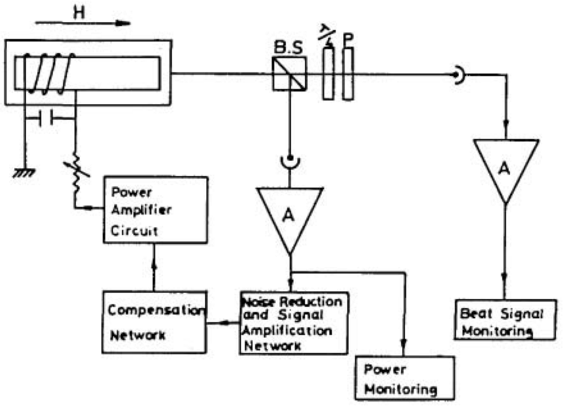

Fig. 2. Block diagram of the experimental apparatus: *B.S.*, beam splitter; *P*, polarizer; *H*, magnetic field; *A*, preamplifier.

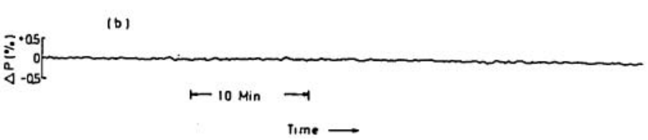

Fig. 3. Typical results for (a) frequency and (b) amplitude stabilization of a Zeeman He–Ne laser by the total power method.

the present method, the laser is stabilized by controlling its cavity length by using I_{total} as the feedback signal. Clearly the length of the laser tube will also be compensated whenever I_{total} changes due to discharge current fluctuations. This results in frequency drift as the cavity length is changed to accommodate these fluctuations. For simultaneous frequency and amplitude stabilization of the laser, the laser tube and power supply must both be relatively quiet.

Comparing with the two known methods for frequency stabilization of a longitudinal Zeeman laser, the frequency discriminator of the total power method is slightly less sensitive. For a given change of laser cavity length, the modulation depth of I_{total} for our test laser is ~30%, while those for ΔI and f_b are, respectively, ~4 and 7 times higher. The sensitivity of this method can be increased by working at a lower magnetic flux density. In this way the region of the gain curve for which the laser is single mode is larger. As a result, the modulation depth of I_{total} is larger. Nevertheless, frequency stability comparable to those achieved by the other two methods has been realized using the present arrangement with proper servo-system design. The present method is advantageous because it does not require a polarizing beam splitter and dual photodetectors as in the ΔI method or polarizer and λ/4 plate as in the beat frequency method. Simultaneous output power stabilization has also been demonstrated. The beat frequency stabilized laser, however, can be easily locked to line center, whereas the present method does not have such a natural reference point. Nonetheless, a Zeeman laser can be locked to its output power extremes in the present method. The frequency resettability of such lasers is currently under study.

This work was partially supported by the National Science Council and the Industrial Technology Research Institute. Ci-Ling Pan would like to thank T.-C. Hsieh and T. N. Chu for helpful comments.

References

1. T. G. Polanyi, M. L. Skolnick, and I. Tobias, "Frequency Stabilization of a Gas Laser," IEEE J. Quantum Electron. **QE-2,** 178 (1966).
2. L. S. Cutler, "Frequency Stabilized Laser System," U.S. Patent 3,534,292 (1970).
3. T. Baer, F. V. Kowalski, and J. L. Hall, "Frequency Stabilization of a 0.633-μm He–Ne Longitudinal Zeeman Laser," Appl. Opt. **19,** 3173 (1980).
4. A Sasaki, S. Ushimaru, and T. Hayashi, "Simultaneous Output- and Frequency-Stabilization and Single-Frequency Operation of an Internal-Mirror He–Ne Laser by Controlling the Discharge," Jpn. J. Appl. Phys. **23,** 593 (1984) and references therein.
5. Ci-Ling Pan *et al.*, "A Comparative Study of Frequency- and Amplitude-Stabilized Two-Mode Internal-Mirror He–Ne Lasers," Proc. Natl. Sci. Council A Taiwan, (to be published) (Jan. 1986).
6. N. Brown, "Frequency Stabilized Lasers: Optical Feedback Effects," Appl. Opt. **20,** 3711 (1981).
7. Ci-Ling Pan and P.-Y. Jean, "Stabilization of Internal-Mirror He–Ne Lasers," accepted for publication Appl. Opt. **25,** May 1 (1986).
8. J. W. Hansen, K. F. Rogers, Jr., and D. E. Thomas, "Amplitude Stabilization of a Single-Mode, 6328A, He–Ne Laser," Rev. Sci. Instrum. **39,** 872 (1968).